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End-pumped Nd:BEL laser performance

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Abstract. Performance data for a cw Nd:BEL laser end pumped by two 500 mW laser diode arrays are presented and compared with the performance data for a Nd:YAG laser in a similar configuration. The phased arrays used as the pump source are cooled by a temperature-controlled heat sink to permit wavelength tunability. Although the absorption bandwidth for Nd:BEL is substantially broader than for Nd:YAG, the Nd:BEL was found to have a higher threshold for lasing. Both rods gave slope efficiencies of 42%. The dependence of the output power on output mirror reflectivity was measured, with Nd:BEL showing a greater sensitivity to reflectivity than Nd:YAG. The optimum reflectivities were found to be 0.98 for Nd:BEL and 0.97 for Nd:YAG. The maximum TEM_{00} cw power achieved for each rod at these reflectivities was 250 mW for Nd:BEL and 283 mW for Nd:YAG. The observed electrical-to-optical conversion efficiency was factored into a product of analytic component terms, and excellent agreement was found between observed and calculated efficiencies. It is concluded that under the conditions used in this work, both BEL and YAG hosts perform comparably. The conditions under which BEL might outperform YAG as a host for diode-pumped Nd are discussed.

Subject terms: lasers; Nd:YAG lasers; diode-pumped lasers; solid-state lasers.

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CONTENTS

1. INTRODUCTION

Recent publications[1,2] reporting laser-diode-pumped Nd:YAG laser development indicate that high overall efficiencies can be achieved with tightly focused end-pumped geometries. Since those reports were published, other researchers have attempted to obtain even higher efficiency by finding alternative hosts for Nd that make better use of the pump diode spectral bandwidth.[3,4] Of the various hosts for diode-pumped Nd lasers, $La_2Be_2O_5$ (BEL) offers several unique advantages. These include a relatively broad spectral absorption bandwidth and a crystal cut for which the rod is athermal. In addition, the crystal growth and polishing technology for this material is relatively mature. The 810 nm absorption peak of Nd:BEL is close to the Nd:YAG absorption band, so in many cases the same diode array pumps can be used for both BEL and YAG hosts.

The absorption spectra using unpolarized light for Nd:BEL and Nd:YAG are shown superimposed in Fig. 1. It can be seen that in BEL not only is the Nd absorption broader than in YAG but it is also stronger in the spectral region of 805 to 820 nm.

We performed a comparative study of laser-diode-pumped cw Nd:BEL and Nd:YAG. We show that both hosts perform well, and we specify under what conditions BEL might be the better host.

2. EXPERIMENT

The outputs of two 500 mW phased arrays were collimated with an anamorphic lens pair and combined using a polarizing beamsplitter cube, as shown schematically in Fig. 2. The arrays used consisted of 40 stripes on a 400 μm emitting length, and their radiation pattern was measured to have a half-angle of 36° perpendicular to the junction and 12° parallel to the junction. The diodes are mounted on heat sinks provided with Peltier coolers for wavelength control. The output spectra of the laser diodes as measured with an optical multichannel analyzer (OMA) show five to six longitudinal modes operating simultaneously, with a total bandwidth of about 1.5 nm. Typical spectra are shown in Fig. 3. With both arrays operating at 500 mW, approximately 700 mW could be focused onto one face of a 1 cm long Nd:host rod. This face had a dichroic coating that was a high reflector (HR) at 1.06 μm and was specified greater than 85% transmissive at 808 nm. The face of the Nd crystal interior to the cavity was antireflection (AR) coated. The focused spot size from each array consisted of two unequal intensity lobes separated by 50 μm; 99% of the pump energy was contained in a rectangular area 75 μm wide by 10 μm high. The output mirror had a 10 cm radius of curvature and was positioned with respect to the rod to provide a nearly hemispherical resonator. The concentration of Nd in each host was 1.1%.

3. RESULTS

3.1. Power

The output power in the IR as a function of laser diode pump power incident on the rod is shown for both hosts in Fig. 4. The comparison was performed using a 95% output coupler. It can

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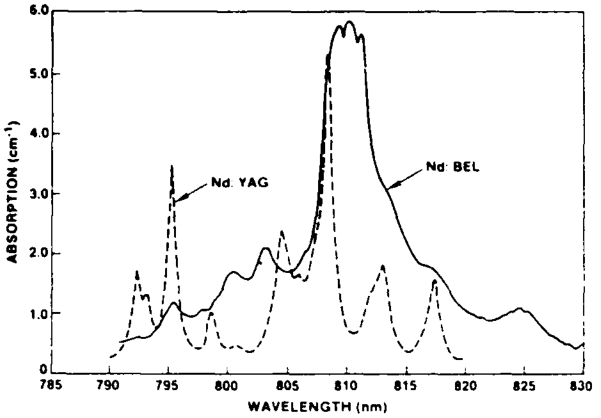

Fig. 1. Absorption spectra in unpolarized light for the 1 cm long rods of Nd:BEL and Nd:YAG used in this work.

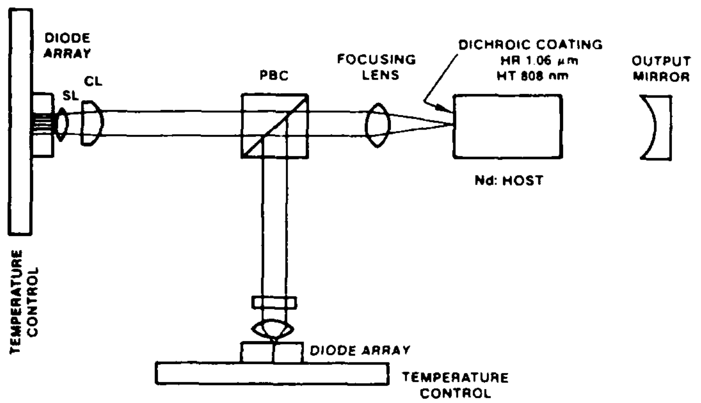

Fig. 2. Schematic diagram of experimental arrangement. SL is spherical lens, CL is cylindrical lens, and PBC is polarizing beamsplitter cube.

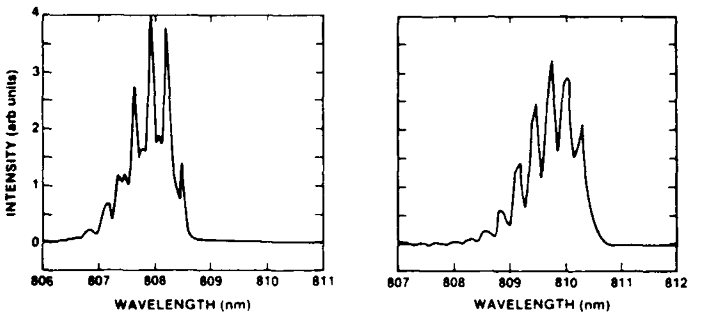

Fig. 3. Emission spectra of the same 500 mW laser diode array at cold sink temperatures of 13°C (left) and 19°C (right). These two temperatures matched the laser diode output to the absorption peaks of Nd:YAG and Nd:BEL. The spectra were taken with an optical multichannel analyzer at a resolution of 1.2 Å with the array operating at full power.

be seen that both rods have a 42% slope efficiency, with BEL having a higher threshold. The polarization of the laser emission was measured for both hosts, and it was found that the YAG emission was essentially unpolarized, while that of BEL was linearly polarized. The dependence of the output power on the output coupling was measured for reflectivities between 95%

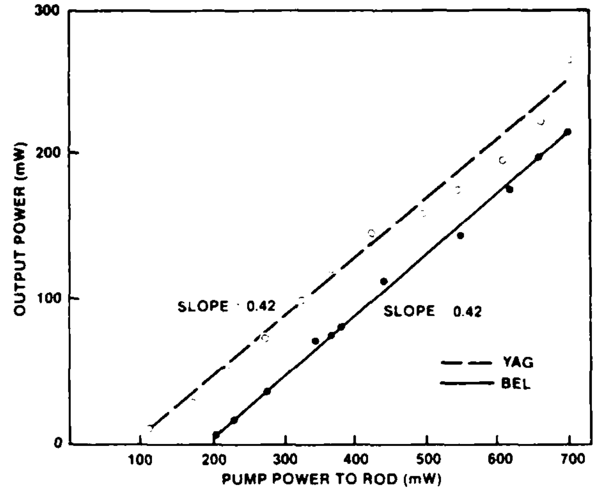

Fig. 4. Laser output power as a function of incident pump power for Nd:BEL and Nd:YAG. Slope efficiency indicated.

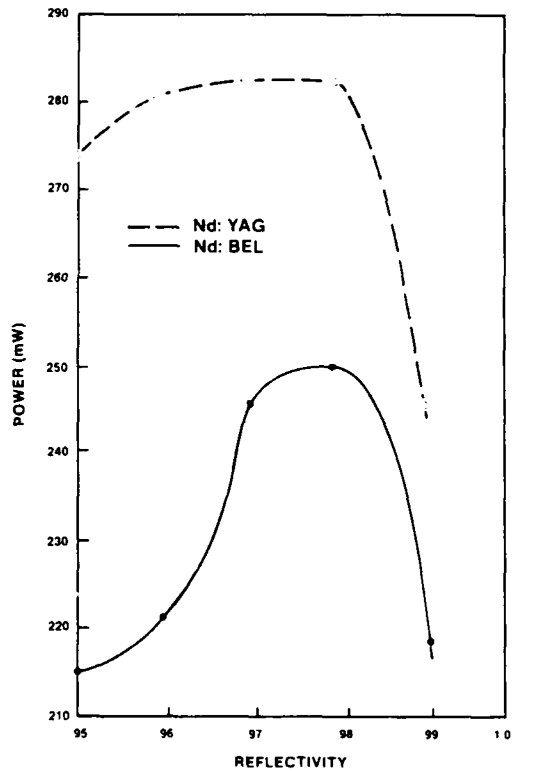

Fig. 5. Dependence of laser output power on output coupling for Nd:BEL and Nd:YAG.

and 99.9%, and the results are shown in Fig. 5. The flatness of the YAG curve contrasts dramatically with the high degree of sensitivity shown by BEL to output reflectivity. A peak output of 250 mW was measured for BEL at 98% reflectivity. The peak for YAG was 283 mW at 97% reflectivity.

The threshold pump power as a function of output coupling was also measured and is plotted in Fig. 6. At 98% the pump threshold for BEL was 92 mW, whereas at 97% the threshold for YAG was 61 mW. From the dependence of the threshold power on the logarithm of the mirror reflectivity one can derive

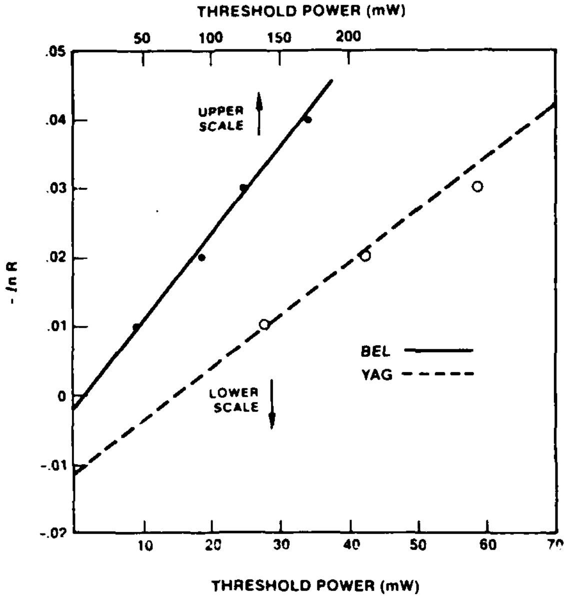

Fig. 6. Threshold pump power as a function of the logarithm of the output mirror reflectivity for Nd:BEL and Nd:YAG. Intercepts give single pass loss of 0.002 for Nd:BEL and 0.012 for Nd:YAG. Slopes are 2.6×10^{-4}/mW for Nd:BEL and 7.7×10^{-4}/mW for Nd:YAG and are related to the small signal gain (see text). Note different abscissa scales for BEL and YAG.

the single pass loss for BEL and YAG (0.002 and 0.012, respectively) and the small signal gain dependence on pump power.[5] The latter is related to the slope of the curves in Fig. 6 by

$$K = \frac{g_0 \ell}{P_{in}} , \tag{1}$$

where 2K is the slope, g_0 is the small signal gain, ℓ is the length of the active medium, and P_{in} is the pump power to the rod. The small signal gain for BEL as calculated in this fashion is one-third that for YAG.[6] The optimum reflectivity for a given pump power can also be calculated from these parameters by

$$R_{opt} \approx 1 - \frac{(2KP_{in}L)^{1/2} - L}{1 + L} , \tag{2}$$

where R_{opt} is the optimum reflectivity and L is the single pass loss. For BEL the calculated optimum reflectivity at 700 mW of pump power is 98%.

3.2. Efficiency

From an empirical point of view one can factor the overall efficiency into the product of three measurable quantities, as shown in Table I for BEL and YAG. The first factor is the electrical to optical pump light conversion efficiency for the laser diode. The efficiencies for the 500 mW arrays used in this work are only 50% of those presently available, and this of course reduces the overall efficiency by the same percentage. The lower efficiency for the diodes used to pump BEL reflects the higher junction temperature needed to wavelength tune to the (red-shifted) absorption peak. The power consumption of the coolers is not included in the overall efficiency. The collection efficiency of the optics is a function of the numerical aperture of the lenses and the reflectivity of the AR coating. The higher number for BEL is a result of using higher quality coatings. The third factor is the pump light to IR conversion efficiency of the laser rod and is given for the optimum output coupling for each host. The lower number for BEL is due to the higher threshold.

TABLE I. Measured efficiency factors for Nd:host lasers.

Host	Electrical to optical conversion 808/810 nm	Collection optics	808 nm to 1.06 μm or 810 nm to 1.07 μm @R	Overall efficiency (%)
BEL	0.135	0.75	0.35 @98%	3.5
YAG	0.170	0.63	0.40 @97%	4.3

TABLE II. Efficiency factors for end-pumped Nd:YAG.

Process	SAIC	This work
Diode efficiency	0.24	0.17
Upper state efficiency (USE)	0.60	0.38
Stokes efficiency	0.76	0.76
Quantum efficiency	0.80	(0.80)
Transfer efficiency	0.98	0.63
Output efficiency (OE)	0.60	0.61
Beamfill factor	0.90	(0.90)
ASE losses	1.0	1.0
Extraction efficiency	0.95	(0.95)
Resonator losses	0.70	0.71
Optical conversion efficiency*	0.36	0.23
Overall efficiency†	0.086	0.039

*Product of USE × OE
†Product of optical conversion efficiency × diode efficiency

The measured efficiencies can be better understood by considering in greater detail the processes affecting the overall efficiency for an end-pumped Nd:YAG laser. A Science Applications International Corp. (SAIC) report[7] provides a basis for this discussion. Table II compares the SAIC results with our measurements.

In Table II the efficiency factors are classified into three categories. The diode efficiency refers to the conversion by the laser diode arrays of electrical power into pump radiation; the upper state efficiency takes into account those factors that affect the transfer of pump energy to the upper laser level; and the output efficiency is a measure of the conversion of the stored upper state energy into 1.06 μm laser radiation. The diode efficiency used by SAIC was based on a McDonnell-Douglas report[8] and was considered typical.

The Stokes efficiency is the upper state efficiency factor for the quantum defect between the pump photon energy and the laser photon energy. The quantum efficiency is the fraction of absorbed photons leading to upper laser level population. This factor was recently measured and reported to lie within the range of 0.6 to 0.8.* The upper end of this range was chosen for the purposes of this table. (Numbers in parentheses in the table indicate quantities not measured in the present work.) It is important to note that the product of the Stokes and quantum efficiencies is 0.61, which represents the maximum "theoretical" slope efficiency for Nd:YAG.

The transfer efficiency is the fraction of pump photons that are absorbed. It is the product of photon transport from the array to the rod and subsequent absorption by the Nd. We can write

$$P_A = P_D \eta_t , \tag{3}$$

*Unpublished data from L. DeShazer, Spectra Technology (1985).

$$\eta_t = [1 - \exp(-\alpha\ell)](1 - r) , \tag{4}$$

where P_A is the power absorbed by the rod, P_D is the power emitted by the laser diode array, η_t is the transfer efficiency, α is the absorption coefficient of the laser rod at the diode wavelength, ℓ is the path length of the pump radiation in the rod, and r summarizes the losses occurring between the pump array and the Nd:YAG rod (i.e., the collection efficiency). Empirically, it is observed that almost all of the pump radiation entering the rod is absorbed, so the transfer efficiency term will be determined by the collection efficiency. We used the value 0.63 from Table I for this number, although this does not take into account the reflection of pump radiation by the dichroic coating on the end-pumped face of the rod. (We also assumed this reflection loss to be 0 in measuring the threshold power and in drawing the abscissa in Fig. 4.) The product of these three terms gives an upper state efficiency of 0.38 for this work.

The output efficiency is the product of four terms, although the amplified spontaneous emission (ASE) losses will be zero for a cw system (i.e., the ASE efficiency is 1). The extraction efficiency will also be high for the cw laser, as shown in the table. The beamfill factor is a measure of the spatial overlap of the resonator mode with the inversion profile created by the pump beam. For the end-pumped configuration this number is nearly 1, although the pump geometry used in this work does not completely match the resonator mode. Instead, a short focal length lens is used to concentrate the pump energy into a small volume that absorbs most of the pump light in the region of spatial overlap.

The resonator loss term can be determined from the single pass loss and output mirror reflectivity by the expression

$$\eta_r = \frac{1}{1 + L/(1 - R)} , \tag{5}$$

where η_r is the efficiency term due to resonator losses and R is the reflectivity of the output mirror. The SAIC results are based on a system presented in Ref. 8; in the present work we use the 0.012 single pass loss determined in the threshold measurements mentioned above to obtain 0.71 for η_r with R = 0.97. The product of these four efficiency factors gives an output efficiency of 0.61.

The product of the upper state efficiency and the output efficiency gives 0.23 for the calculated optical conversion efficiency. Since the optical conversion efficiency takes into account all efficiency factors except the diode efficiency, this number can be compared with the measured value of 0.25 (the product of the third and fourth columns of Table I for Nd:YAG). This agreement is quite satisfying and gives at least circumstantial credence to the estimated values shown in parentheses in Table II. The overall efficiency shown in Table II is the product of the optical conversion efficiency and the diode efficiency, and therefore the calculated value will also be close to the measured efficiency of Table I.

3.3. Second-harmonic conversion

Using an intracavity lens and a KTP crystal, we obtained several milliwatts of green light from both YAG and BEL. The conversion efficiencies were extremely low (on the order of 1%) owing to reflection losses by the lens coating and alignment sensitivity of the resonator. Operation of the BEL cavity with polarization compensation did not result in improved performance, presumably because of the sensitivity of the output to additional intracavity losses introduced by the polarization rotator (Fig. 5). The one benefit of the poor conversion efficiency was that longitudinal mode coupling[9] was not observed, and as a consequence good amplitude stability of the second-harmonic output was obtained.

4. DISCUSSION

The broader absorption bandwidth in BEL does not enhance its performance, but this might have been anticipated in an end-pumping configuration in which the absorption path length is long and the spectral bandwidth of the laser diode arrays is relatively narrow. The difference in threshold pump fluence for the two hosts can be understood by considering the factors important for end pumping. Several expressions for these factors appear in the literature.[10–13] The expression from Ref. 11 is

$$P_{th} = \frac{\pi h\nu_p(w_\ell^2 + w_p^2)}{4\sigma f_2\tau[1 - \exp(-\alpha\ell)]}(L + 1 - R) . \tag{6}$$

In this equation ν_p is the pump frequency, w_ℓ and w_p are the laser beam and pump beam radii, respectively, σ is the gain cross section, f_2 is the fraction of the total $^4F_{3/2}$ population in the upper laser level, τ is the upper state lifetime, and α is the same as in Eq. (4).

The beam radii are similar for the two rods, and assuming that f_2 is also approximately the same for YAG and BEL, Eq. (6) indicates that the ratio of the two laser thresholds goes as

$$\frac{L + 1 - R}{\sigma\tau} . \tag{7}$$

Using the optimum reflectivities and the single pass losses obtained in this work, we can evaluate the ratio. The lifetimes for BEL and YAG are 150 and 230 μs, respectively, and the gain cross section[6] for BEL is 2.1×10^{-19} cm^2. The cross section for YAG is less well known; Ref. 5 puts it in the range 2.7×10^{-19} to 8.8×10^{-19} cm^2. Our results indicate a value of 3.4×10^{-19} cm^2 (see below). With these values the ratio of pump threshold power is calculated to be 1.3, which is close to the measured value of 1.5. We note that the threshold power can also be calculated using the measured resonator parameters from

$$P_{th} = \frac{L - \ln(R)}{2K} . \tag{8}$$

This expression gives 1.5 as the ratio of threshold powers.

It is important to emphasize that for side pumping or for pumping with broader spectral bandwidth arrays, the broader absorption in BEL will become a positive factor affecting its performance. However, since BEL is a biaxial crystal, the absorption is highly polarization dependent. In the present experiment we found that either array operating alone had approximately the same threshold power even though their polarizations were crossed. Under conditions other than the tight focusing end-pumped configuration, one would need to consider the orientation of the crystal axes relative to the polarization of the pump beam.

The slope efficiencies for the laser output versus pump input can be calculated for the two hosts from the measured slopes of the curves in Fig. 6, the stimulated emission cross sections, and the fluorescence lifetimes. From Ref. 5 we can derive an expression for the ratio of the slopes for BEL and YAG,

$$\frac{m_B}{m_Y} = \frac{K_B}{K_Y}\frac{\eta_B}{\eta_Y}\frac{\sigma_Y\tau_{fY}}{\sigma_B\tau_{fB}} , \tag{9}$$

where

$$\eta = \frac{2(1 - R)}{(R)^{1/2}[L - \ln(R)]} \tag{10}$$

is the output coupling efficiency, m is the slope efficiency, and the subscripts B and Y refer to BEL and YAG. Using the measured values for K and L and the stimulated emission cross section for BEL, we observe that for the two slope efficiencies to be equal, the stimulated emission cross section for YAG must be 3.4×10^{-19} cm^2. This is close to the value reported in Ref. 6.

Although Eq. (9) makes it appear that the slope is inversely proportional to the $\sigma\tau_f$ product, K itself is directly proportional to $\sigma\tau_f$, with the constant of proportionality being the product of the diode and upper state efficiency factors shown in Table II. In addition, for R near 1, Eq. (10) reduces to Eq. (5). This leads to the conclusion that the slopes for the two hosts are equal because the efficiency factors shown in Table II for YAG are close to those for BEL. The lower stimulated emission cross section and the shorter fluorescence lifetime for BEL affect the threshold power and the optimum output coupling but do not affect the differential slope efficiency. As was mentioned, because of the sharp dependence of the output power on mirror reflectivity, the BEL resonator was more sensitive to intracavity losses caused by additional elements needed for doubling, but at higher pump powers this is anticipated to become less of a problem.

In the present experiment, 700 mW of pump power provided 283 mW of laser power, leaving approximately 60% of the pump beam energy to go into thermal heating of the lattice and spontaneous emission losses. In considering the relative merits of the two hosts it is important to recognize that a minimum of 24% (corresponding to the quantum defect) and perhaps as much as 39% (if the quantum efficiency also contributes) of the pump radiation is converted to heat, so athermal BEL might be the preferred choice at high pump fluence.

With regard to improving the overall efficiency of either host, the two lowest factors in Table II are the diode efficiency and transfer efficiency. The diode efficiency can be approximately doubled with presently available devices, and the transfer efficiency can be increased to perhaps as high as 90% with well coated and corrected optics. These two improvements alone would produce an overall efficiency of almost 12%.

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